**Project**:     **Laboratory <u>Tests of Gravity at the Dark Energy Length Scale</u>**

**Personnel:**

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**Goals:**

The observed dark-energy density $\rho_E$ of about 3.8 keV/cm$^3$ corresponds to a length $\lambda = [h\,c\,/(2\pi\rho_E)]^{1/4} \approx 85$ μm that may be a new length fundamental scale. Direct tests of the properties of gravity at and below this length scale are very challenging because of the extremely small forces involved. However, such tests should have a high priority because new gravitational phenomena could be revealed. For example, Sundrum[1] and others have suggested that the observed "tiny" value of the dark energy (compared to the quantum-mechanical vacuum energy) could be explained if gravity "shuts off" at separations small compared to $\lambda$. We propose to make such tests, probing the inverse-square law at length scales down to 30 μm. If a violation is observed we will then perform Equivalence Principle tests to further characterize the new physics. Our torsion-balance techniques are currently the only ones with demonstrated sensitivity to see gravity at length scales below 1 mm.

**Precursor Developments:**

Tests of the inverse-square law at very short length scales face two major challenges:
1) achieving the sensitivity to measure reliably the very small gravitational force between tiny test bodies
2) eliminating backgrounds from non-gravitational sources that are inherently vastly stronger than gravity.

We have demonstrated expertise at such tests. We developed a series of novel "missing-mass" torsion-balance instruments for testing the gravitational inverse-square law at sub-millimeter length scales. The test bodies in these instruments are small holes bored into azimuthally symmetric rings. Following the original 10-hole device, discussed in Hoyle et al.[2], we implemented a series of upgrades to that apparatus; each of which was a significant improvement over the Hoyle et al. instrument. The latest of these, shown in Figure 1, uses 21-fold rotational symmetry and many other instrumental improvements to obtain the constraints shown in Figure 2. This work, which is the thesis experiment of Dan Kapner[3], has been reported at conferences and will be submitted for publication shortly. The 95% confidence exclusion plot of that experiment, indicated in Fig 2., is limited not by our sensitivity, but by the fact that we are detecting a short-range r*epulsive* signal (a weakening of gravity) that is not currently understood. Lamoreaux has suggested that this could be a manifestation of the finite-temperature Casimir force, but calculations indicate that our electrical shield attenuates this force below our sensitivity limit.

**Existing Support:**

This work is primarily supported by the NSF, and secondarily by the DOE. Our NSF support is under pressure because of NSF's commitment to LIGO.

**Experimental Design:**

A new Yukawa interaction with a range small compared to the relevant dimensions of an instrument like ours will produce a torque

$$N = \alpha \, G \, (\Delta A / \Delta \phi) \, \lambda^3 \, \exp(-r / \lambda) \,,$$

where $(\Delta A / \Delta \phi)$ is the change in attractor/detector overlap area with respect to the attractor angle, and $\alpha$ and $\lambda$ are the strength and range of the Yukawa interaction..

The sensitivity of our "multi-hole" designs is nearing practical limits. We have analysed a new design that overcomes the limitations of the "multi-hole" designs by featuring much stronger signals for new physics. This "Fourier-Bessel" (so-called because the Newtonian and Yukawa signals can be computed analytically using the Fourier-Bessel series) is based on detectors and attractors whose "test bodies" are thin, slender sectors of circles as shown in Figure 2. The attractor and detector are 50 μm thick annual sheets of Rhenium (density = 21.04 g/cm$^3$) that each have 180 sectors removed by electric discharge machining. The very high azimuthal symmetry number ($m$=180) substantially attenuates the Newtonian signal and enhances the signal from short-range Yukawa interactions. The short-range Yukawa signal is further enhanced by high density of Rhenium (which has $\rho_1 \rho_2$ 4.4 times greater than the Molybdenum used in the Kapner et al experiment). These Rhenium foils will be bonded to a flat substrate and mounted in the instrument as shown in Figure 2. The "Fourier-Bessel" pendulum will have less than half the mass of the Kapner et al. pendulum. This will allow us to improve our thermal noise by using a thinner torsion fiber (the noise is dominated by anelastic losses in the torsion fiber).

**Expected Error Budget:**

We have made a Monte-Carlo simulation of the proposed experiment, assuming that finite-temperature Casimir forces can be attenuated sufficiently by our electrical shield. (This point is discussed below.) This code successfully predicts the constraints obtained from the Kapner et al. experiment. The main limiting factors are the noise (which increases above the thermal limit at detector-shield separations below 100 μm) and correlations between the values of key experimental parameters which are only know to finite accuracy. Our absolute calibrations use the gravitational octupole interaction between three small spheres mounted on the detector and three larger spheres mounted 15 cm away—a distance close to that where G was recently measured in our laboratory. Our new experiment will have 2 independent ways to measure the most important experimental parameter which is the detector/attractor separation. We will measure it using the electrical capacity as was done in our previous work, but also by incorporating

*m*=18 components to our attractor and detector mass distributions. The gravitational signals from these two mass distributions fall off exponentially with separations but with very different slopes determined by their very different azimuthal symmetries.

**Project's Strength and Risk Areas:**

The project's strength is obvious—there is little doubt that it will have the sensitivity to test the gravitational inverse-square law at length scales down to 30 μm.

We identify two risk areas:

1) Finite-temperature Casimir forces between the detector and attractor may not be sufficiently shielded by our 10 μm thick copper shield to take full advantage of our sensitivity. We are currently investigating this point theoretically. We can always subtract away such effects by running with attractors and detectors of the same shape made from Aluminum. Detailed calculations show that this will have essentially the Casimir force but any gravitational signals will be heavily suppressed by a factor $(\rho_{Re}/\rho_{Al})^2 = 60$. In the longer term, low-temperature operation would greatly reduce the Johnson noise in our test bodies, which drives the finite-temperature Casimir effect.

2) We may be initially prevented from achieving detector—attractor separations as small as we expect—either because we cannot make the detector and attractor as flat as we expect or because of detector bounce (induced by seismic vibration). These problems have technical solutions that can be implemented but which would delay the result.

**Timeline:**

We expect that this work will be finished in about three years-i.e. in fall 2008. The first two years will be devoted to fabricating the attractor and detector which require some technical R&D to meet the required flatness requirements.
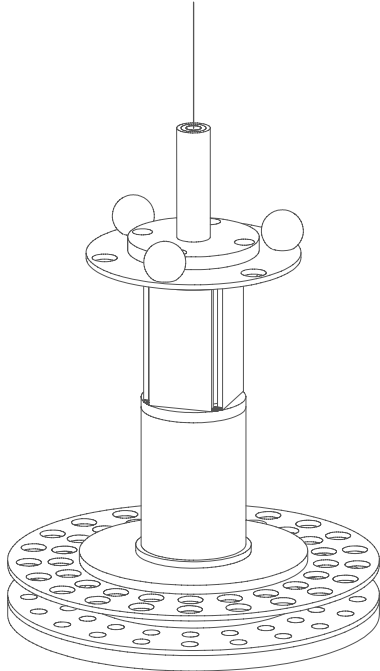
**Figure 1:** Schematic drawing of the detector and attractor used in the Kapner et al. experiment. The "test bodies" are the 2 ranks of 21 holes in the pendulum and attractor. The attractor, situated slightly below the detector (a torsion pendulum), rotates continuously, exerting a gravitational torque on the detector that oscillates 21 times for each revolution of the attractor. The attractor actually consists of two plates joined together. The lower plate contains another set of 21 holes (not visible in this drawing) shifted azimuthally by 360/21 degrees. This largely cancels the torque from Newtonian gravity, but has little effect on a short-range interaction simply because the lower plate is too far from the detector. A 10 μm thick copper foil (not shown) stretched between the detector and attractor forms part of an essentially hermetic electrical shield surrounding the detector. The 3 small sphere near the top of the detector are used to make an absolute gravitational calibration of our torque scale.
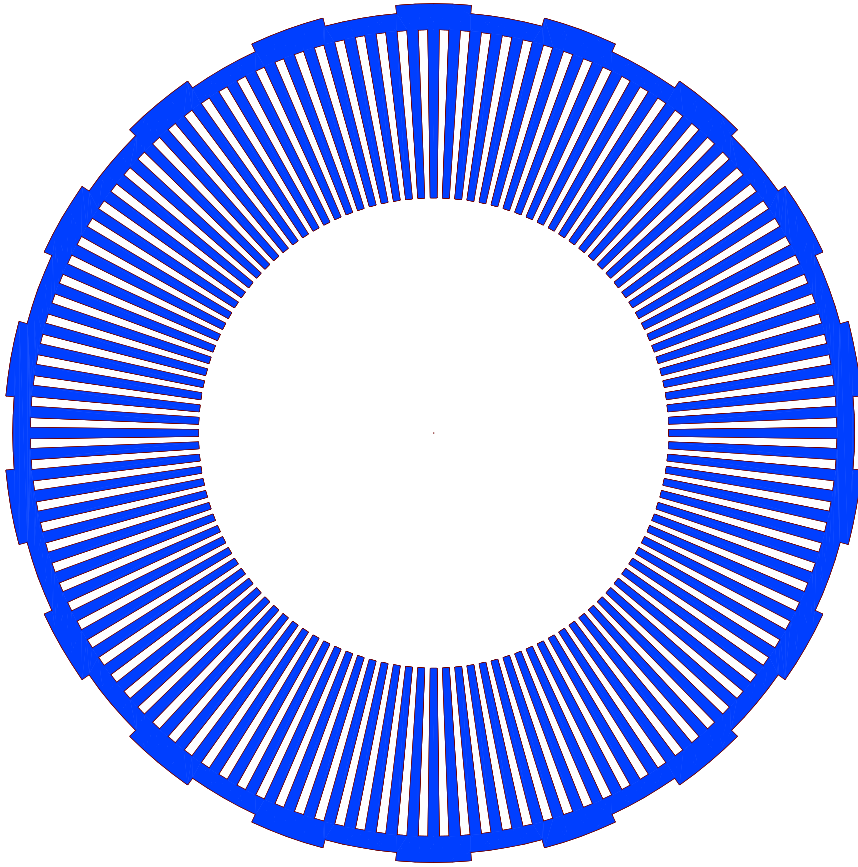
**Figure 2:** Plan view of the attractor and detector for the proposed "Fourier-Bessel" apparatus. These are identical 50 μm thick high-density discs with outer diameters of 5.1 cm. The "test bodies" are the cutouts that combine $m$=180 and $m$=18 symmetries.
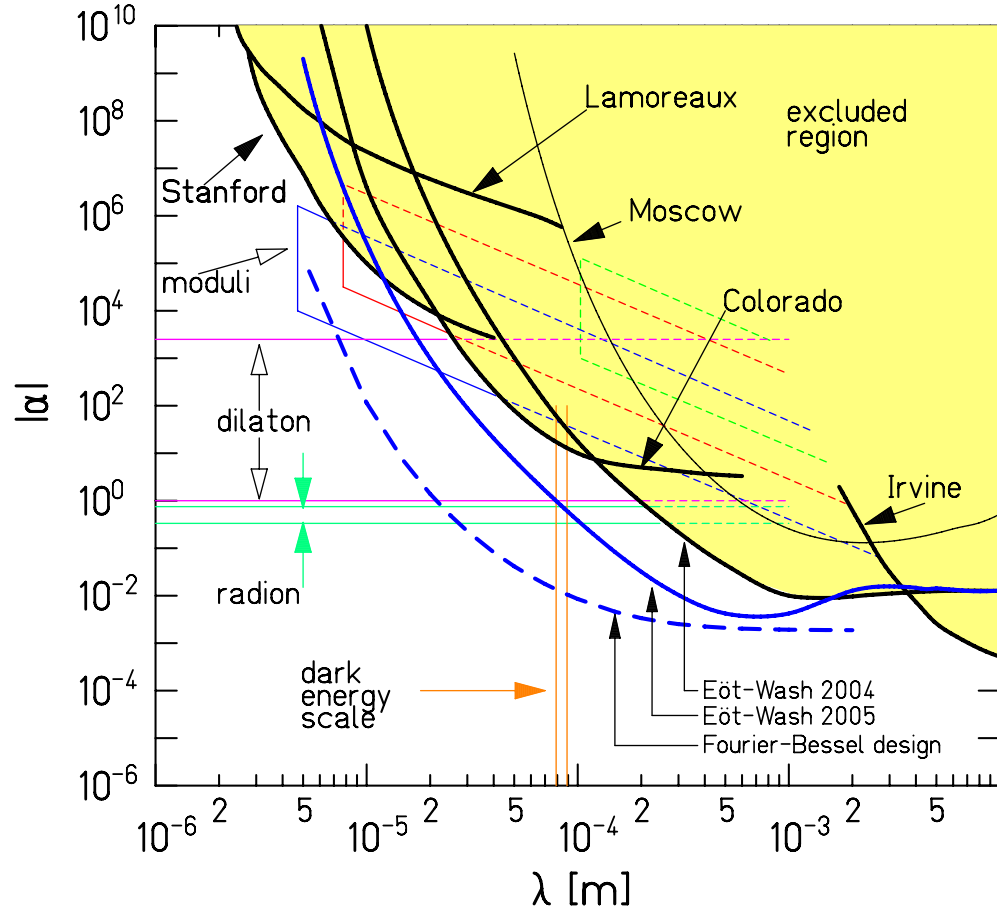
**Figure 3:** Upper limits on violations of the gravitational inverse square law with a form $V(r) = - G\, m_1\, m_2\, /\, r\, (1 + \alpha\, \exp(-r/\lambda))$. The region above the heavy solid line is excluded at 95% confidence. The Hoyle et al. constraint is denoted by Eöt-Wash 2004, the Kapner et al. constraint by Eöt-Wash 2005. The goal of this project is indicated by the heavy dashed line.

[1] R. Sundrum, Phys. Rev. D **69**, 044014 (2004)
[2] C.D. Hoyle et al., Phys. Rev. D **70**, 042004 (2004)
[3] D.J. Kapner, unpublished PhD thesis, University of Washington (2005)